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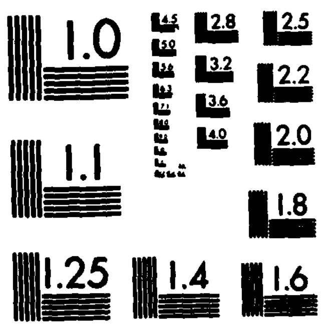

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ACOUSTIC EMISSION WAVEFORMS IN A HALF SPACE

Masayasu Ohtsu* and Kanji Ono

Department of Materials Science and Engineering,
School of Engineering and Applied Science,
University of California, Los Angeles, California 90024.

* Now at the Department of Civil Engineering,
Kumamoto University, Kumamoto, 860 JAPAN.

ABSTRACT

A generalized theory of acoustic emission (AE) is developed on the basis of the theory of elastodynamics and dislocation models. Acoustic emission sources are represented as dislocation sources and include both discontinuities of displacement components and tractions. As AE waves are observed at a stress free surface, Green's functions in a half space are obtained. Fortran programs for computing these functions for non-Cauchy solids are used to calculate AE waveforms from a point crack and moving cracks. Their implication on current attempts of determining source characteristics via deconvolution is discussed.

INTRODUCTION

Detailed analysis of acoustic emission (AE) waveforms has been difficult, because of the high freqeuncy range of AE signals. Quantitative evaluation of AE signals as well as theoretical attempts to predict AE originating from sources with prescribed characteristics have been made. The theory of AE still faces difficult problems, the most serious of which is the absence of Green's functions for relevant geometries.

The theory of AE must be able to specify the nature of a source starting from a given displacement (or velocity) history at a defined point of observation. Earlier, theories of dislocations and elastodynamics were applied to simple analysis of AE generation /1-3/, but only in an infinite medium. For any AE analysis, this is unsatisfactory as a stress-free surface must exist where emissions are detected. AE in a half space (in a semi-infinite body) is a good representation of special experiments /4,5/. Pekeris /6/ obtained an analytical solution of Green's function in a half space for a Cauchy solid (Poisson's ratio = 0.25). Methods of generalized ray, normal modes and integral transforms have been used to obtain a limited number of solutions for a plate /7-9/. In most of these calculations, an AE source was represented by a force impulse or force couple. While this representation is appropriate in calibration experiments that utilize a force step, the characterization of most AE sources requires displacement steps. In an infinite medium, the spatial derivatives of Green's functions are used in conjunction with displacement functions. However, the presence of a stress-free surface makes this practice untenable. The spatial derivatives of Green's functions in a half space or of a plate cannot be given in an analytic form and require elaborate procedures even in numerical computations.

In the present paper, we summarize a generalized theory of AE /10,11/ for the representation of source characteristics. It is based on the integral formulation of elastodynamics and the dislocation theory. We have employed Fortran programs for the calculation of Green's functions in a half space for a surface pulse and for a buried pulse. These computer programs can also compute Green's functions of the second kind, which are suitable for the applications to AE waveform simulation. Several dynamic cases are considered.

<u>GENERALIZED THEORY OF AE</u>

We present a generalized theory of AE using the integral representation of a solution in elastodynamics /11,12/. Let D denote a domain occupied by a given body in the three dimensional space and S denote its boundary surface. With the assumption of linear isotropic and homogeneous elastic body, an elastodynamic problem is to solve the following equation in D;

$$L[u_i(x,t)] = (\lambda + \mu)u_{j,ji} + \mu u_{i,jj} - \rho \ddot{u}_i = 0, \tag{1}$$

where $u_i(x,t)$ is a displacement field at position, x, and time, t, and the comma indicates a differentiation ($u_{i,i} = \partial u_i/\partial x_i$). L[ ] represents a differential operator and is used to simplify expressions, λ and μ are Lame constants and ρ is the mass density. Since the effect of a body force usually is not dominant in elastodynamic problems, we omit the term of a body force in equation 1.

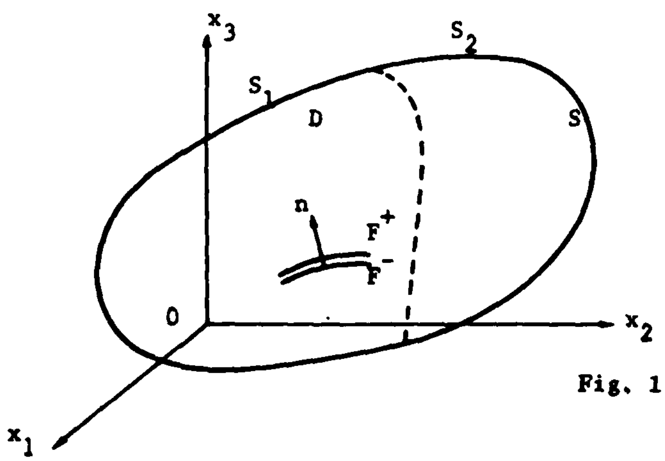

Fig. 1 Dislocation surface F situated in elastic body D, surrounded by boundary S ($S = S_1 + S_2$).

The solution of equation 1 is subject to the initial conditions of a quiescent past on D + S and boundary conditions on S. Boundary S consists of S_1 and S_2, where displacement g_i is given on S_1 and traction h_i is given on S_2, as follow:

$$u_{i(x,t)} = g_i(x,t) \qquad \text{on } S_1$$

$$T[u_i(x,t)] = \lambda u_{k,k}n_i + \mu(u_{i,j}n_j + u_{j,i}n_j) = h_i(x,t) \qquad \text{on } S_2.$$

Here n_i is the outward normal vector on S. Note that T[ ] is also used as a *differential* operator that describes a relationship between a displacement field and a traction.

For two arbitrary displacement fields $u_i(x,t)$ and $v_i(x,t)$ in domain D, the reciprocity theorem of elastodynamics states

$$\int_D (L[u_i(x,t)]*v_i(x,t) - L[v_i(x,t)]*u_i(x,t))dV$$

$$= \int_S (T[u_i(x,t)]*v_i(x,t) - T[v_i(x,t)]*u_i(x,t))dS, \tag{2}$$

where * means a convolution integral with respect to time. Green's function G_{ij} is then defined as a solution of the following equation:

$$L[G_{ij}(x,t;x',t')] = -\,\delta_{ij}\;\delta(x-x')\delta(t-t'). \tag{3}$$

Setting u_i as a solution of equation 1 and v_i to be G_{ij} in equation 2, we obtain the following integral form as a solution of equation 1,

$$u_i(x,t) = \int_S (G_{ik}(x,t;x',t')*t_k(x',t') - T_{ik}(x,t;x',t')*u_k(x',t'))dS. \tag{4}$$

where we define $T[u_k] = t_k$ and $T[G_{ik}] = T_{ik}$. T_{ik} indicates a traction

associated with a displacement field of Green's function G_{ik} and sometimes is called Green's function of the second kind. It is expressed as follows:

$$T_{ij} = \lambda G_{ij,j}n_k + \mu G_{ik,j}n_j + \mu G_{ij,k}n_j$$

Next, consider a domain containing a dislocation. We assume homogeneous boundary conditions on S ($g_i = 0$ on S_1 and $h_i = 0$ on S_2) and consider another boundary F (dislocation surface) as shown in Fig. 1. We apply equation 4 to domain D surrounding boundaries S_1, S_2 and F, and the following equation results:

$$u_i(x,t) = \int_F (G_{ik}(x,t;x',t')*f_k(x',t') + T_{ik}(x,t;x',t')*[u_k(x',t')])dF. \tag{5}$$

Equation 5 represents any kind of dislocation sources, and provides the generalized representation of AE source mechanisms. Generally speaking, discontinuities of displacement and of traction exist on a dislocation surface. However, it is likely that one or the other has a dominant effect on AE waveforms. Therefore, equation 5 can be simplified to contain either the first or second term in the integrand, or

$$u_i(x,t)) = \int_{-\infty}^{\infty} dt' \int_F G_{ik}(x;x',t-t')f_k(x',t)dF, \tag{5a}$$

$$u_i(x,t) = \int_{-\infty}^{\infty} dt' \int_F T_{ik}(x;x',t-t')[u_k(x',t')]dF. \tag{5b}$$

Denoting the elastic constant as C_{pqrs}, $T_{ik}*[u_k]$ can be expressed as

$$T_{ik}*[u_k] = C_{pqrs}*G_{ip,q}[u_r]n_s.$$

Unfortunately, $G_{ip,q}$ is impossible to calculate analytically unless the medium is infinitely bounded. In cases of interest to AE analysis, it is therefore imperative to use equation 5b by directly calculating T_{ik} numerically. When surface area F can be regarded as infinitesimal compared with domain D, the surface integral in equation 5 is evaluated only at a source point x' and is equal to ΔF. Depending on the types of dislocations, equations 5a and 5b with the initial conditions of a quiescent past can be simplified to the following convolution integrals:

$$u_i(x,t) = \Delta F \int_0^t G_{ik}(x;x',t-t')f_k(x',t')dt', \tag{6}$$

$$u_i(x,t) = \Delta F \int_0^t T_{ik}(x;x',t-t')[u_k(x',t')]dt'. \tag{7}$$

A discontinuity of the traction component, f_k, in equation 6 is equivalent to a point force. Consequently, equation 6 is employed to analyze wave motions subject to an applied force, such as the breakage of a glass capillary and a pencil lead. This equation is useful in the transducer calibration, but not appropriate for the analysis of AE waveforms due to microfracturing events (although it can be used with added difficulties). For the latter, it is preferable to use equation 7. Here, a discontinuity of displacement component is directly related to the formation of a crack or any dynamic movement in a material. By using equation 5b or 7, we can account for a moving dislocation that represents an incremental extension of a precrack using the same method as the fault model in the synthesis of seismograms /13/.

Considering the method of AE observation, we need solutions of equations 5 to 7 at a stress-free surface. In order to analyze AE waveforms by equations 6 and 7, we find that a solution of equation 3 is a Green's function in a half space which can be substituted into the two equations. In real experiments, a propagating medium is a finite body so that corresponding Green's functions cannot be obtained easily. However, wave motions in a half space are obviously observed before reflected waves arrive at the observation point. Thus, the present method can provide the initial parts of AE waveforms except in very thin plates and complex structures.

GREEN'S FUNCTIONS IN A HALF SPACE

The problem of determining the elastic disturbances resulting from a point force in a half space is known as Lamb's problems. Green's functions in a half space are only available as numerical solutions, and these solutions cannot readily be applied to problems of interest in AE studies. The programs for computing Lamb's solutions were given elsewhere /11/. By using these programs, vertical surface motions of a stress-free surface due to a step function force on the same surface or that due to a buried source have been calculated /11/.

AE WAVEFORMS DUE TO CRACKS

a. A Point Crack

Using the program for a buried source with revised external functions, we computed a Green's function of the second kind, T_{ik}. We simulated AE waveforms using this solution and equation 7. The dislocation model chosen for this study is the case of a tensile crack parallel to the surface, or a Mode I crack. The unit normal n_i of the dislocation surface F is identical to the x_3-axis, and a displacement of the dislocation has only a $[u_3]$ component. From equation 7, the resulting displacement is expressed, as follows:

$$u_3(x,t) = T_{33}(x,t;x't)*[u_3(x',t')] = (\lambda G_{31,1}+\lambda G_{32,2}+(\lambda + 2\mu)G_{33,3})*[u_3]. \qquad (8)$$

The spatial derivatives of Green's functions, such as $G_{31,1}$, $G_{32,2}$, and $G_{33,3}$ are computed separately, again revising external functions. In order to investigate the applicability of this method, we computed the epicenter response of T_{33}, which is due to a displacement discontinuity of a step function. The result is shown in Fig. 2.

By using the following time function /14/, we simulated AE waveforms:

$$\left[\ddot{u}(t)\right] = \cos^3\left(\frac{\pi}{\tau} t - \frac{\pi}{2}\right) \sin\left(\frac{\pi}{\tau} t - \frac{\pi}{2}\right) \qquad \left(0 \le t \le \tau\right)$$

Results are shown in Fig. 3. The rise time τ was assumed to be 750 ns. An epicenter response (x_3 = 2.4 cm) and a response at x_1 = 6 mm and x_3 = 2.4 cm are calculated to examine the effect of a shift of a source or the location of a transducer. It is interesting that due to a small shift of a source or a transducer, the amplitude of the P-wave decreases and the S-wave becomes stronger. Other effects of varying rise time, different observation points and source functions can be calculated by this procedure.

b. A Moving Crack

Considering sequential shifts of the dislocation surface ΔF in equation 7 or using equation 5b, we can introduce effects of a moving crack. This can readily be evaluated by using equation 5b or 7, but not easily accomplished by

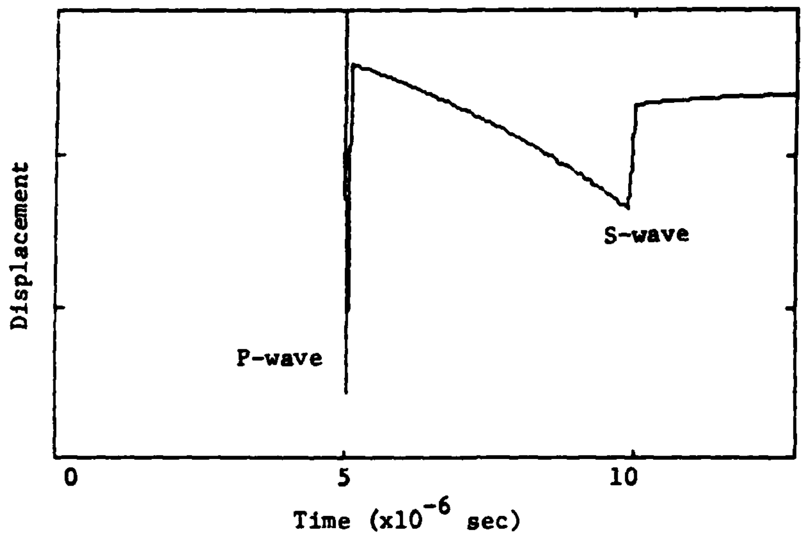

Fig. 2 Green's function of the second kind T_{33} for a buried source at the epicenter.

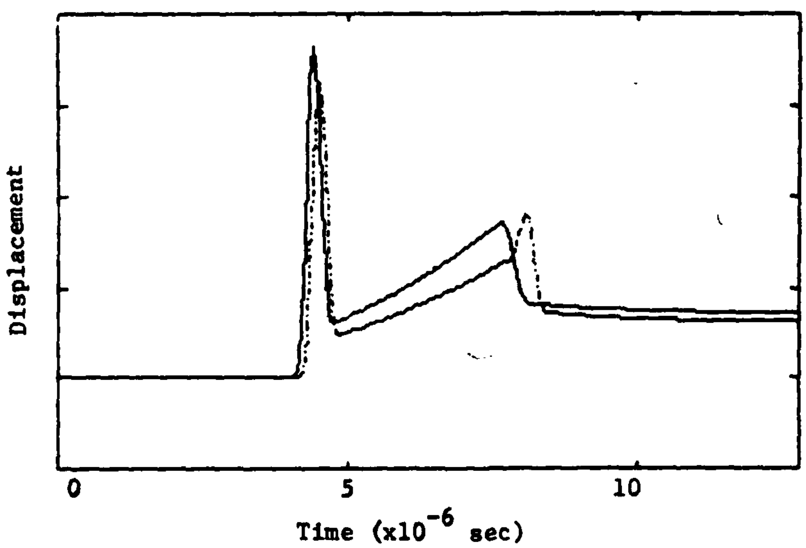

Fig. 3 A simulated waveform of AE corresponding to the dislocation model representing a stationary Mode I crack (rise time of the source function = 750 ns). A solid curve shows a response at an epicenter at 2.4 cm above the crack and a broken curve shows a response at a point 6 mm from the epicenter.

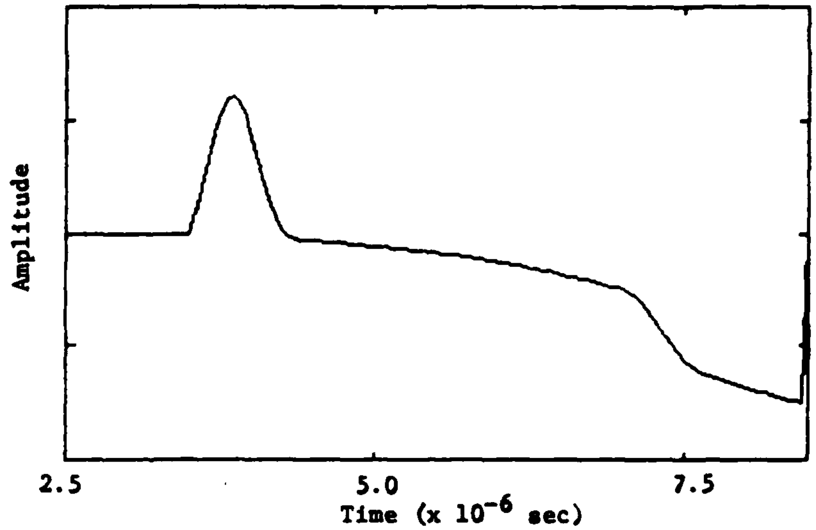

Fig. 4 A simulated waveform due to the moving crack model giving $[u_3]$. (The rise time 1 μs, a length of the dislocation 0.2 mm and the rupture velocity 500 m/s).

means of equation 5a or 6. The crack moves 0.2 mm in the x_1-direction of at a uniform velocity of 500 m/s. This is represented by four sequential applications of a source displacement on the crack surface at four points in the x_1-direction. The same source function as in Fig. 3 was employed and the rise time was 1 μs. The result is shown in Fig. 4. In comparison to the displacement waveform due to a single crack given in Fig. 3, we can see that the presence of a moving crack broadens the peaks of the displacement response and decreases the amplitude of the S-wave. The comparable experimental result of Wadley and Scruby /15/ agrees with the displacement curve for the moving crack quite well.

DISCUSSION

Source characteristics of acoustic emission have been investigated as the inverse problems using the deconvolution analyses /15/. In these studies, Green's functions of a point crack were used to deconvolve AE waveforms observed at certain points of observation. The effect of a moving crack can be significant on the inverse problem and needs to be examined. As we showed in the preceding section, the moving crack broadened the AE waveform. When a faster crack velocity was used, the AE waveform was closer to that of Fig. 3. Obviously, one must use the dynamic Green's function in deconvolution analysis of any observed AE waveforms. In the conventional deconvoluton analysis, one is forced to use the Green's function of a stationary point crack and it is impossible to take into account the effect of a moving crack or dislocation.

In order to investigate the extent of errors due to the dynamic nature of cracks on the inverse problems, we performed deconvolution analyses of simulated AE waveforms. Simulated waveforms were transformed into the frequency domain by fast Fourier transform (FFT) and were divided by the corresponding Fourier spectrum of Green's functions of the second kind for a stationary point crack. These deconvoluted waveforms in the frequency domain were transformed into the time domain by inverse FFT. Four examples are shown in Fig. 5. These are deconvolved source functions obtained from four cracks. One was a stationary point crack and the other three were dynamic cracks with the rupture velocities V_r of 2000 m/s, 1000 m/s, and 500 m/s. Amplitudes are normalized in those graphs.

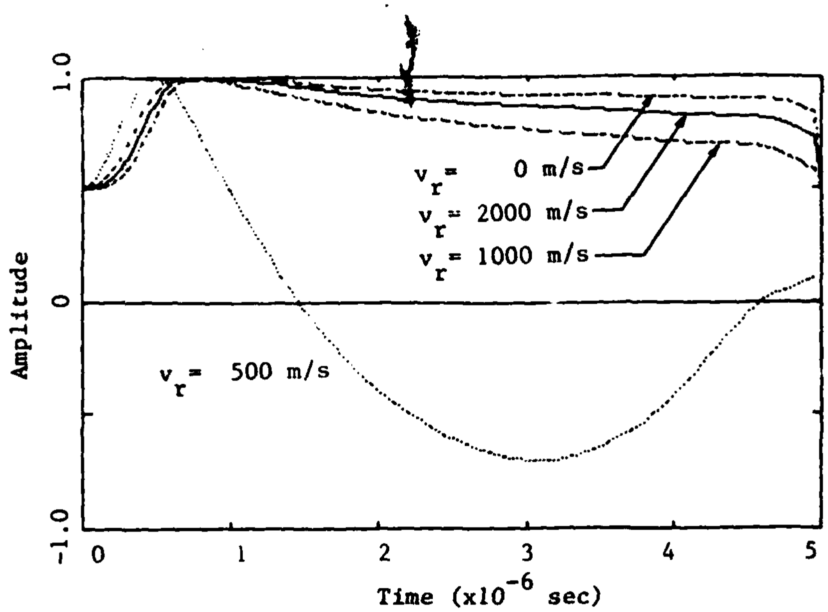

Fig. 5 Source time functions recovered from simulated AE waveforms for the moving cracks. For the cracks with the rupture velocities V_r of 2000, 1000, 500 m/s and a stationary crack.

The deconvolved waveforms for the stationary crack and those of two fast rupture velocities recovered the essential features of the source function. However, gradual decreases in displacement amplitudes were observed beyond the original rise time of 1 μs. This decrease wa exaggerated in the case of the slow crack with V_r of 500 m/s. In this case, the amplitude became strongly negative at 3 μs. This behavior apparently arises from the summations of waveforms from different sources staggered in space and time. Since one has no a priori knowledge of the source waveform, conventional deconvolution using Green's function of a stationary source may lead to unrealistic source functions.

CONCLUSIONS

1. A generalized theory of AE is presented in this paper. Applying the reciprocity theorem of elastodynamics to a domain containing a dislocation, displacement fields due to two components of the AE source function are expressed by two integrals. One represents AE due to an applied force step. The other represents AE due to a discontinuity of displacement components on the dislocation surface, which corresponds to a crack or slip.

2. In order to analyze realistic conditions of AE detection, Green's functions of the second kind in a half space are numerically calculated by Fortran programs. Several representative cases are investigated, including a stationary (Mode I) crack and a moving crack.

3. Simulated AE waveforms from dynamic sources can be easily obtained using the present approach. Displacement response from a moving crack is calculated.

4. Commonly used methods of deconvolution of acoustic emission waveforms can produce grossly misleading conclusions. While a point crack response can be deconvolved successfully, the deconvolution of a moving crack responses may lead to wrong source characteristics. More extensive analysis of the "forward" problems should be made before attempting the "inverse" problems.

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REFERENCES

1. K. Malen and L. Bolin, phys. stat. sol.(b), 61 (1974) 637-645.

2. J.D. Aachenbach and J.G. Harris, J. Appl. Mech., 46 (1979) 107-112.

3. Y.H. Pao, Elastic Waves and Nondestructive Testing of Materials, AMD-29, Am. Soc. Mech. Engr., New York, 1978.

4. F.R. Breckenridge, C.E. Tschiegg and M. Greenspan, J. Acoust. Soc. Am., 57 (1975) 626-631.

5. H.N.G. Wadley and C.B. Scruby, Advances in Acoustic Emission, ed. H.L. Dunegan and W.F. Hartman, Dunhart Publishers, Knoxville, 1981, pp. 125-153.

6. C.L. Pekeris, Geophysics, Proc. Nat. Acad. Sci., 41 (1955) 629-639.

7. Y.H. Pao and A.N. Ceranoglu, J. Appl. Mech., 48 (1981) 125-147.

8. R.L. Weaver and Y.H. Pao, J. Appl. Mech., 49 (1982) 821-836.

9. N. Vasudevan and A.K. Mal, "Response of an Elastic Plate to Surface Loads," to be published.

10. M. Ohtsu, "Acoustic Emission Characteristics of Concrete and Fundamental Mechanisms," Ph.D. Thesis, Kyoto University, Kyoto, 1982.

11. M. Ohtsu and K. Ono, J. Acoustic Emission, 3 (1984) 27-40.

12. A.C. Eringen and E.S. Suhubi, "Elastodynamics," Linear Theory, Vol. 2, Academic Press, London, 1975.

13. K. Aki and P.G. Richards, Quantitative Seismology Theory and Methods, W.H. Freeman and Company, San Francisco, 1980.

14. M. Ohtsu, J. Acoustic Emission, 1 (1982) 103-112.

15. H.N.G. Wadley and C.B. Scruby, "Elastic Wave Radiation from Cleavage Crack Extension," AERE, Harwell, Oxfordshire, AERE-10351 (1982).

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